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DEVELOPMENT OF A PORTABLE ICE THICKNESS SENSOR

TP 4887E
Transportation Development Centre,
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By

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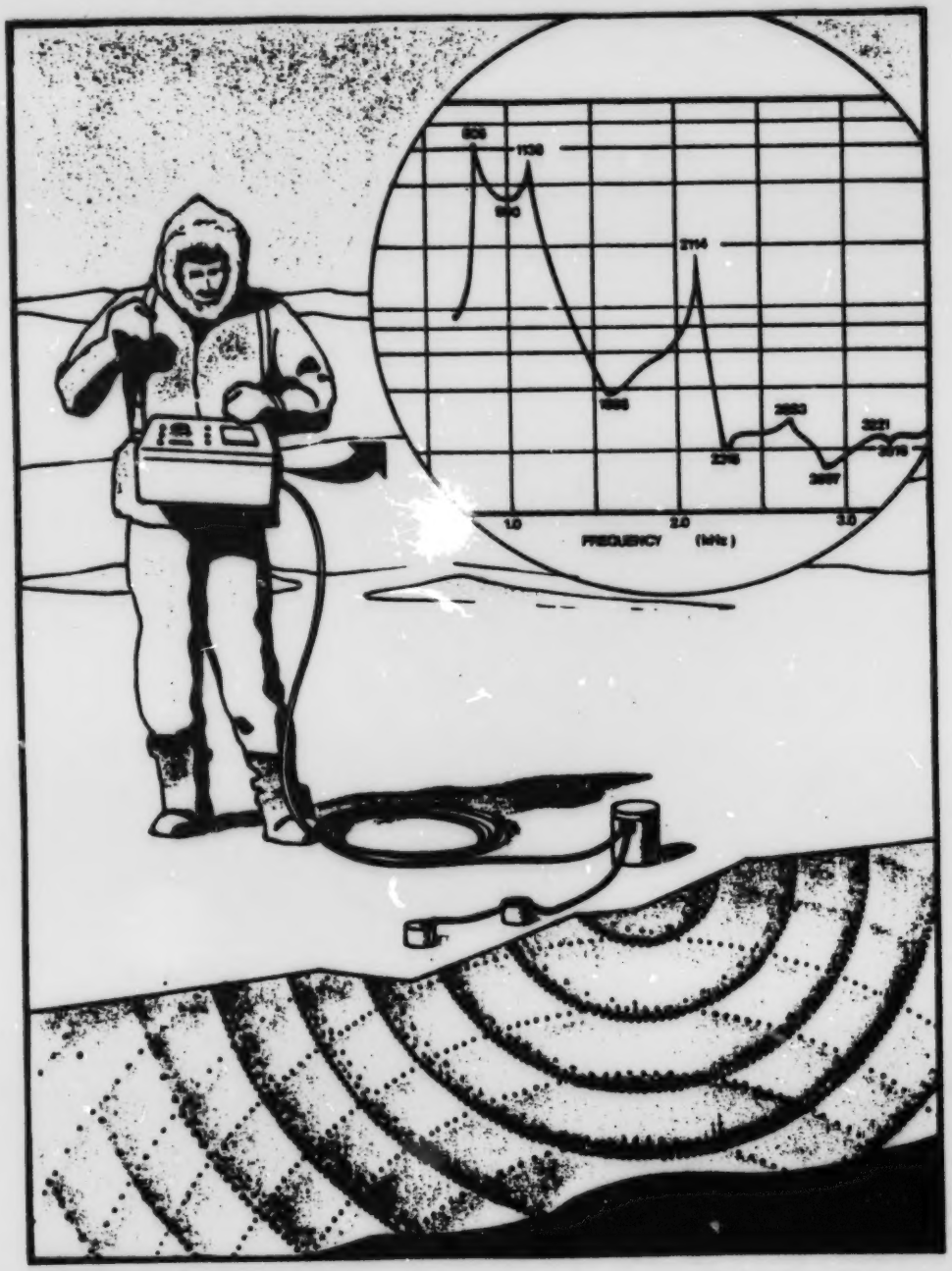

FRONTISPIECE

Artist's impression of the portable ice thickness sensor currently under development. The report describes the evaluation of the theoretical aspects of the system, together with hardware specifications of the instrument.

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17. Abstract

This report describes the investigation of a method of measuring the thickness of floating ice sheets using an acoustic resonance technique. The ice sheet is continuously activated by using a variable-frequency sonar coupled to the top surface, rather than employing a single-shot, seismic approach. Standing waves (resonance) occur at the eigen frequencies and their amplitudes are detected using high-frequency geophones. An off-the-shelf unit was built and used to test the basic principles, initially in water, then on lake ice, and finally on large-diameter ice cores in a cold room. Research showed that acoustic attenuation presents no problem, that the source may be coupled effectively to the ice, and that the resonant harmonics have adequate signal-to-noise levels to be detected without difficulty. After suitable redesign, the technique may be used as a rapid method of measuring floating ice sheets in the thickness range of 0.5 m to 20 m with an error of ±10%.

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17. Résumé

Ce rapport décrit la recherche faite sur le moyen de mesurer l'épaisseur des glaces flottantes uniformes à l'aide des ondes sonores. Il serait fait appel à un sonar à fréquence variable capable d'exciter de façon continue la surface des glaces plutôt que d'utiliser l'approche sismique où l'on procède par impulsion unique. Aux fréquences propres (de résonance), des ondes stationnaires sont engendrées que des géophones haute fréquence permettent de détecter. Un appareil sommaire a été construit et utilisé pour vérifier le bien-fondé des principes de base, d'abord dans l'eau, ensuite sur des glaces de lac et enfin sur des carottes de glace de grand diamètre entreposées dans des chambres froides. La recherche a montré que l'affaiblissement acoustique ne pose aucun problème, que la source sonore peut être effectivement couplée à la surface de la glace et que les harmoniques aux fréquences propres ont un rapport signal sur bruit assez élevé pour qu'elles puissent être aisément détectées. Une fois affinée, cette méthode pourrait servir à mesurer rapidement l'épaisseur des glaces flottantes uniformes dans une fourchette entre 0,5 et 20 m, avec une marge d'erreur de ± 10 pour cent.

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REPORT ON THE WORK CARRIED OUT TO DEVELOP A PORTABLE ACOUSTIC ICE THICKNESS PROFILER

Under the terms of Contract No.4893, File No. D1460-126-7 for Transportation Development Centre, Transport Canada, Montreal.

SUMMARY

Under the terms of a Service Contract issued by the Transportation Development Centre, Montreal, Polar Tech Ltd undertook to carry out an evaluation of a technique to measure the thickness of floating ice sheets of varying thicknesses between 0.2 and 20 metres using resonating acoustic waves.

In its simplest configuration, an ice-mounted sonic source was excited by a precise frequency within the band 300 - 10,000 Hz, and the reflection amplitudes of the ice sheet were monitored. For a given propagation velocity, the resonant fundamental and subsequent harmonics (or eigen frequencies) are directly proportional to the wavelength and hence the ice sheet thickness. Thus, the ice thickness may be determined simply by observing the resonant harmonics.

The project may be broken down into 4 parts: (1) an electronic system was researched, assembled and tested from off-the-shelf equipment, (2) the unit was used to carry out acoustic studies on pseudo-ice (water columns, concrete blocks, etc), (3) the system was then applied to lake and glacial ice to test more complex acoustic principles and de-bug the hardware, and finally, (4) the technique was applied to large ice-cores in the controlled environment of a cold room.

The findings of this evaluation study show that:

1. It is possible to measure sheet ice thickness over the range 0.5 - 20 m with an accuracy of $\pm$10% (or less) without difficulty.

2. An acoustic-based system will provide a compact and cheap way to analyse ice thickness.

3. With further research, it will be possible to improve the sensitivity of the system so that its dynamic range may be expanded to cover the span of 0.1 - 20 m of ice.

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Polar Tech Ltd thanks the Park Superintendent at Jasper National Park for permission to work on the Athabasca Glacier and environs, and Brewster Coach Lines Ltd for lending a tracked vehicle for the on-ice work. Finally, we wish to record our thanks to the staff of Capital Ice Ltd, Victoria who permitted the use of one of their cold rooms for over a month during the final phase of the project.

1. APPLICATIONS OF AN ACOUSTIC ICE THICKNESS PROFILER

Historically, there have been only two methods of measuring ice thickness with any degree of accuracy: either the operator drills a series of holes (a slow and laborious process), or a GSSI impulse radar system (or equivalent) may be used (which is large, expensive and ice-type dependent).

Both techniques have been used widely despite their disadvantages, because the thickness of floating ice sheets is perhaps the most fundamental parameter required when operating in the Canadian North on ice runways, roads, harbour works and shipping lanes.

In 1977, Dr Rick Hudson became interested in using acoustics as an alternative method to measure ice thicknesses, and from then until 1981 he carried out a series of experiments and analyses to test this hypothesis. Early work centred around high frequency seismics (200 - 1000 Hz), but the work was inconclusive because of the nature of sea ice. Ice is frequently cracked, irregular and erratically crystalised, so that the single shot technique of seismics produced too few solutions to too many unknowns. In 1982, he therefore turned to the acoustic resonance method, a technique which had been used to good effect in the 1950's by mechanical engineers to measure steel thicknesses.

The advantages are obvious; since the frequency range is swept slowly, many samples are taken and averaged at any discrete wavelength. The method does not suffer from the drawbacks of ultra-seismics, where a solution is derived from a single shot.

The same applies to the signal source; because it is continuous, it is simpler to build and operate than a pulsed device. Since the thicknesses are relatively small, return times are very short (typically less than a millisecond), requiring specialised equipment to record one-shot techniques. With a continuously emitting source, however, this requirement is not necessary, and the hardware benefits from the simplicity of design.

2. THEORETICAL ASPECTS

The velocity of a longitudinal wave depends upon the dimensions of the specimen in which the waves are travelling. If the solid is a thin bar of finite cross section, then the analysis for longitudinal waves is the same as for a gas, except that the bulk modulus of the gas is replaced by the Young's modulus Y, the ratio of the material's longitudinal stress to longitudinal strain.

The wave equation may then be written :

$$\frac{\partial^2 \eta}{\partial x^2} = \frac{1}{c^2} \cdot \frac{\partial^2 \eta}{\partial t^2}$$

where the wave velocity $c = Y/p$, η = the particle displacement.

A longitudinal wave in a medium compresses that medium and distorts it laterally. Because a solid can develop a shear force in any direction, such a lateral distortion is accompanied by a transverse shear. The effect of this on the wave motion in solids of finite cross section is somewhat complex; in bulk solids, we may treat the longitudinal and transverse waves separately.

The ratio of the transverse stress to the transverse strain replaces the elasticity component in the propagation of pure transverse waves in a bulk solid. The effect of this transverse rigidity is to stiffen the solid and increase the elastic constant governing the propagation of longitudinal waves. The elasticity is increased by an amount equal to Lame's elastic constant lamda in the case for ice, (where the Poisson ratio is 0.3), so that longitudinal waves in a bulk solid have a higher velocity than the same waves along a thin specimen.

Compounded to this effect is the characteristic increase in density of deeply layered materials such as glacial ice, which will also result in an increase in the wave velocity with depth. Bennett and Bentley (1965) found this to be the case in Antarctic ice sheets, where the propagation velocity was related to the bulk density by the relationship:

$$V(p) = 3250 \times p$$

where V(p) was in m/s and p in gm/cc. See Figure 1.

There appears, also, to be a relationship between compressional wave velocity in ice and the presence (or absence) of brine within the solid. Work by Bogorodskii (1958), Brown (1962) and Kohnen (1972) all showed some evidence of the phenomenon, as is illustrated in Figure 2. However, there are a number of grey areas with regard to the brine volume estimation. A variety of methods exist to derive the brine content, rather than

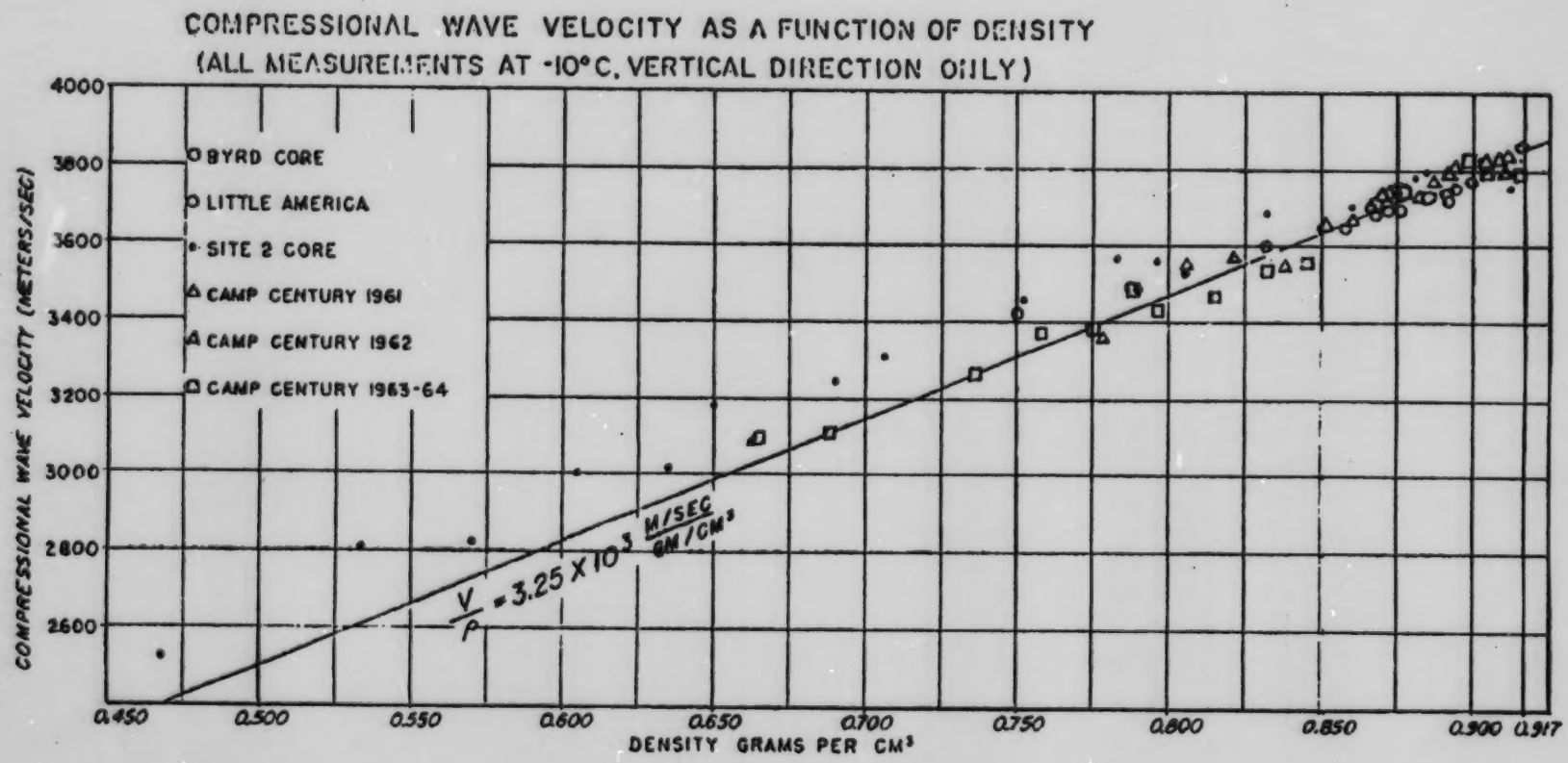


FIGURE 1. Graph showing the relationship between the compressional wave velocity and density for a number of non-saline sites in Antarctica (after Bennett & Bently 1965).

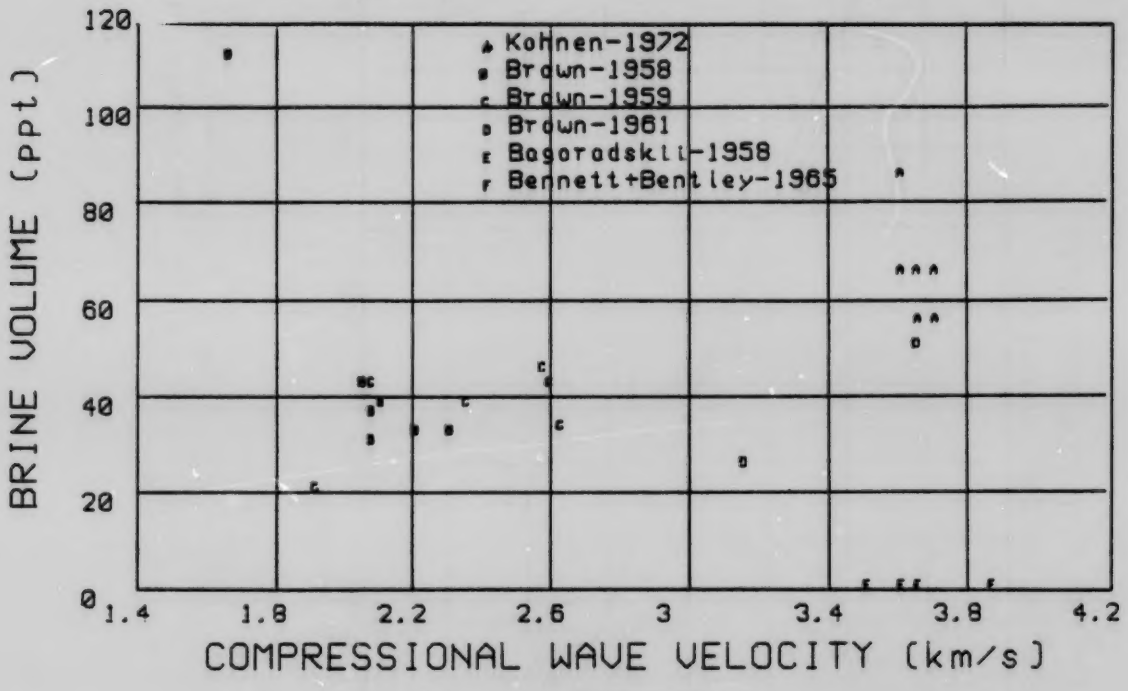


FIGURE 2. *Graph showing a collation of the work of several researchers who have investigated the relationship between the compressional wave velocity (P wave) and brine volume.*

the salinity of a sample, and the researchers seldom specified which technique they used. In addition, it is likely that the salinity was not considered to be of much significance, so that it may have had further errors introduced at the time of sampling. The wave velocity is illustrated with respect to brine volume because it takes into consideration the temperature at the time of the test:

$$\text{Brine volume } B = S\,(45.917/T + 0.93)$$

for S the salinity, T the temperature.

In addition to the variation in wave velocity with dimension (bulk or thin section), density (from snow at the top to hard ice at the base of a glacier), and salinity/brine volume, research has shown acoustic wave propagation through a crystalline structure such as ice exhibits first and fourth order attenuation characteristics. Bogorodskii (1958) noted two effects: he successfully identified the elastic hysteresis phenomenon and deduced from the Stokes-Napier equation that it was frequency dependent, but he was unable to explain the Rayleigh scattering (which he described as heat losses) because of limited data.

However, his work laid the foundation for the use of ultrasonic pulse techniques to determine ice thickness, by Anderson (1958), Brown (1962), Langleben and Pounder (1970), Hoare (1979) and others. Prentiss et al (1965) carried out a series of field tests to determine the sound spectrum of floating ice sheets in their natural state. This permitted background levels to be established based on the dynamics of the area under study, and showed that much of the acoustical energy is retained in the seismic band of 0.1 - 100 Hz. This led to work by Nevel (1968) on the characteristic vibrations of floating ice sheets. He found that the critical frequency was small and the amplification of the stresses at this frequency to be low.

Talibouet (1975) studied the effect on the wave velocity of plastically deforming ice, and noted that the attenuation increased with deformation. His other contribution was the use of methyl-4-1-pentane as a coupling medium between ice and transducer, a technique which was used by Kurfurst (1976) to study ultrasonics in permafrost soils.

The determination of precise attenuation in homogeneous lake ice and its relationship was calculated by Westphal (1965) to be a first and fourth order function of the form:

$$\text{Attenuation } A = 4.5 \times 10^{-2} f + 2.2 \times 10^{-10} f^4$$

where the attenuation is in dB/m and the frequency in kHz. This is shown graphically in Figure 3 and shows that at near-audio frequencies the attenuation losses within a bulk ice sheet will be

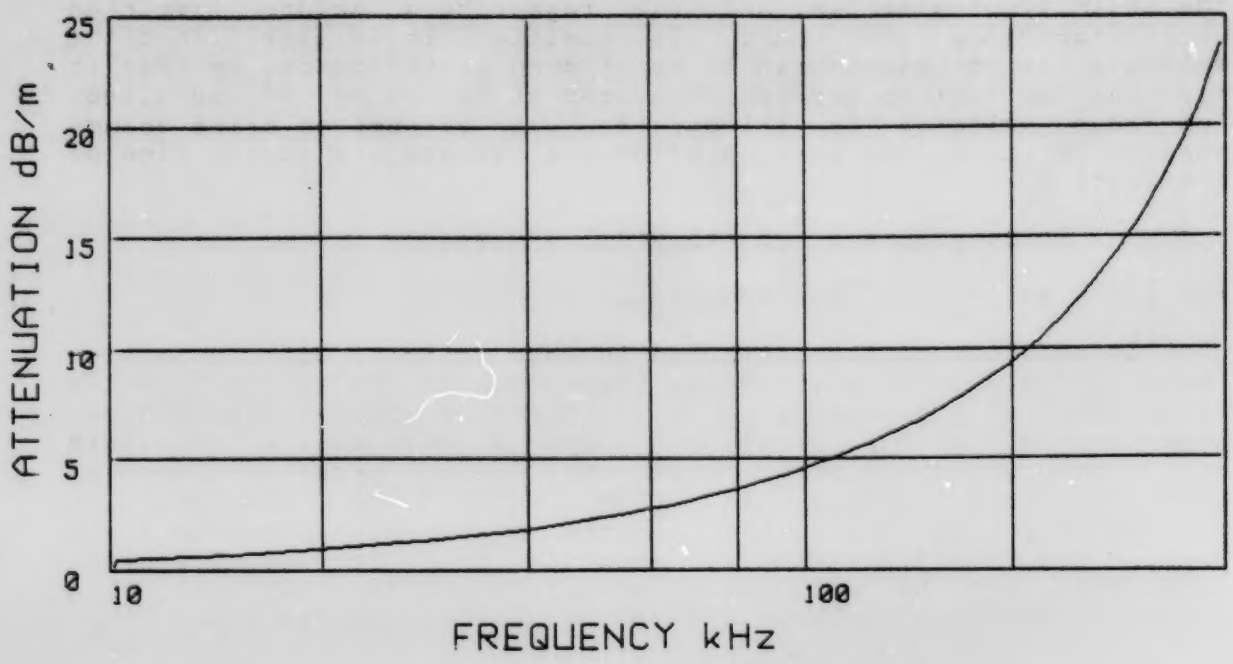


FIGURE 3. Relationship between the frequency of sound and its attenuation in ice, which may be written as a fourth order polynomial. Note that at low frequencies, the attenuation is linear (hysteresis effects), while at shorter wave lengths the attenuation increases as a 4th power due to Rayleigh scattering.

It is therefore possible to expect low losses when sounding through ice in the acoustic band, with nearly 90% of the degradation being due to poor reflections at the ice:water interface.

It follows that if shear waves could be easily generated (to date, no such technique exists), they would offer excellent signal levels since, by definition, they are totally reflected at the water interface.

only slightly affected by path-length. More than 80% of the energy in a transverse wave is lost at the ice:water boundary. Power levels when sounding in either thick or thin ice are therefore much the same.

Field investigations carried out by Langleben (1969) and Langleben & Pounder (1970) confirmed these findings, subject to better definition of the ice type being investigated. Attempts to use this characteristic to measure ice thickness using pulsed waves were only marginally successful because of the complex returns. Vance (1972) tried to overcome this by using the slower, better reflected shear waves: Hoare (1981) tried a beam focussing device. Neither were very effective.

When a planar sound wave meets an acoustic boundary seperating two media normally, part of the wave is transmitted through the boundary and the remainder is reflected back. If the wave approaching the boundary does so through a solid having an acoustic impedence $R(1) = p(1) \times c(1)$ where $p(1)$ is the material's density and $c(1)$ its wave velocity, and part of the wave is transmitted into the new medium with $R(2) = p(2) \times c(2)$, then the displacement of the incident wave $y(1)$ is:

$$y(i) = A(1)\, e^{j\omega(t - x/c_1)}$$

and the reflected wave's displacement:

$$y(r) = B(1)\, e^{j\omega(t + x/c_1)}$$

The reflection coefficient has an amplitude = $B(1)/A(1)$

The transmission coefficient amplitude is = $A(2)/A(1)$

In terms of energy, the total energy in the wave for w the wave frequency is:

$$E = \tfrac{1}{2} p w A$$

Therefore, $$\frac{\text{reflected energy}}{\text{incident energy}} = \frac{[R(1)-R(2)]^2}{[R(1)+R(2)]^2}$$

And, $$\frac{\text{transmitted energy}}{\text{incident energy}} = \frac{4\, R(1)\, R(2)}{[R(1)+R(2)]^2}$$

At an infinite impedance change (as in free space), all the energy will be reflected, with a 180° phase change occurring in the amplitude.

Solution of the wave equation shows that for a standing wave condition (resonance):

$$y = Ae^{j\omega t}(e^{-j\omega(x/c)} - e^{j\omega(x/c)})$$

$$= (-2j)Ae^{j\omega t} \sin(\omega x/c)$$

Solving this equation shows that the permitted frequencies are:

$$\omega(n) = \frac{n\pi c}{l}$$

where n = 1 is the fundamental, and n = 2,3,... are the harmonics.

Notice that if the acoustic impedance of medium 1 is greater than that of medium 2 (as in the case of an ice:water interface), then the incident particle velocities are in phase, but the acoustic pressures are 180° out of phase.

Note also that almost 90% of the energy of a normal wave travelling through sea ice is transmitted into the water below while only 10% is reflected. This is to our advantage provided sufficient energy may be coupled to the ice at the surface, because it permits spurious harmonics and complex reflections to be damped rapidly. Similarly, nearly 100% of the energy in the ice is reflected at the upper ice:air boundary.

3. EXPERIMENTS AND RESULTS.

3.1 Equipment.

Calculations show that to set up resonant waves in an ice sheet having an average compressional wave velocity of 3200 m/s and varying in thickness between 0.5 m and 20 m, it is necessary to have an acoustic system capable of delivering an output over the frequency range 150-12,000 Hz. Such systems are available since that is the prime hi-fi range. Problems do arise, however, in the choice of a resonating device.

Various loudspeakers and transducer systems were investigated. A prime consideration was that the unit should deliver a minimum of 50 watts rms and that its response be flat over the frequency band of interest. Additional conditions were that the device be rugged (which ruled out commercial moving-cone devices), capable of being immersed in water (which ruled out electrostatic speakers as a choice) and portable (which excluded the use of most piezo-crystals).

The result was the selection of a moving coil underwater speaker built by a British firm. It fulfilled most of the conditions listed above. Specifications are given in Appendix I. The Gearing & Watson UW60 Loudspeaker had several additional features: it came complete with a step-down transformer so that it could be driven by long cable lines at 100 volts without signal loss, it was the smallest unit investigated by Polar Tech Ltd, and it was one of the less expensive devices capable of delivering 60 watts rms.

Tests were run in deep water to determine whether the device met its specifications of level output across the audio band. A Hermes Sonabuoy Hydrophone was used in the field. This was itself pre-calibrated against a Gould CH-1A serial No.2280 hydrophone (Figure I.1). The results showed that the UW60 did not follow the manufacturer's specifications (which are shown in Figure I.2). Gearing & Watson carried out their test in the A.M.T.E test tank, UK, and found that their unit deviated only $\pm$7 dB ref 1 microbar over the frequency range of interest. Our tests showed (Figure I.3) that there was a very substantial bulk resonant peak at 700 Hz which increased the deviation to $\pm$15 dB. This was still almost 3 times better than any other device investigated, and was considered to be acceptable.

The UW60 was mounted inside a 6 inch PVC pipe such that its cone was set back a safe distance from the bottom surface, to avoid damage from pointed objects when placed on the ground. A rubber membrane was then stretched across the bottom open face, and the pipe filled with a mixture of water and antifreeze. This served to achieve three things: (1) since the unit was effectively

'under water', the loudspeaker could be driven with higher power settings, (2) the fluid and membrane served to couple to the ice more efficiently, and (3) by first passing the sound through a liquid, no shear wave components could be transmitted to the ice sheet. Although slower and less attenuated than compressional waves, the presence of both shear and compression waves would have made subsequent data analysis considerably more complex.

To drive the loudspeaker, a special signal generator was developed using the XR-2206 chip. This permitted a variety of carefully controlled wave shapes to be used to drive the signal source to determine whether better coupling, penetration and/or resonance was possible with one type of wave or % mixture of waves. Work both in water columns, ice cores and lake ice show that there are no appreciable differences, and that a conventional sine wave suffices adequately.

The signal source was amplified using a portable (dc powered) public address (PA) amplifier, capable of delivering 100 watts into a 100 V line. In this way, it was possible to drive very long cables without signal loss. It was anticipated that during field trials, that the electronic equipment would be kept in the relative warmth of a vehicle while the speaker and receivers were carried out onto the ice to carry out the tests.

The response of the total transmit side of the system is shown in Figure 4. Notice that the natural resonance of the speaker is still apparent at about 700 Hz, but is now much reduced, and the overall system response is excellent.

The choice of signal receiver resulted in a variety of devices being tested to determine suitability. Piezo-electric devices were excluded because of their damped characteristics and poor coupling to ice. Two Mark Products L-40 A-2 geophones were selected because they were (a) water-tight, (b) very rugged, (c) had good response characteristics up to 600 Hz on their specification sheet (see Appendix II) and were easy to interface into existing equipment. Subsequent investigations showed that their upper band response was adequate to 2 kHz but poor to 10 kHz. This roll-off could be compensated for, in part, in the subsequent pre-amplifier and main amplifier stages.

Each geophone was supplied in a 'rock mount', a flat disk of aluminum to which the device is bolted. This allows the unit to sense over a wider area, and therefore reduces the effect of surface waves in favour of vertically polarized ones. By using 2 devices in tandem, the effect is further reduced. Concern at the outset of the project that the suface waves would mask the much weaker vertical weaves proved to be groundless; the undamped nature of the ice ensured that resonant harmonics greatly exceeded the backround surface wave levels.

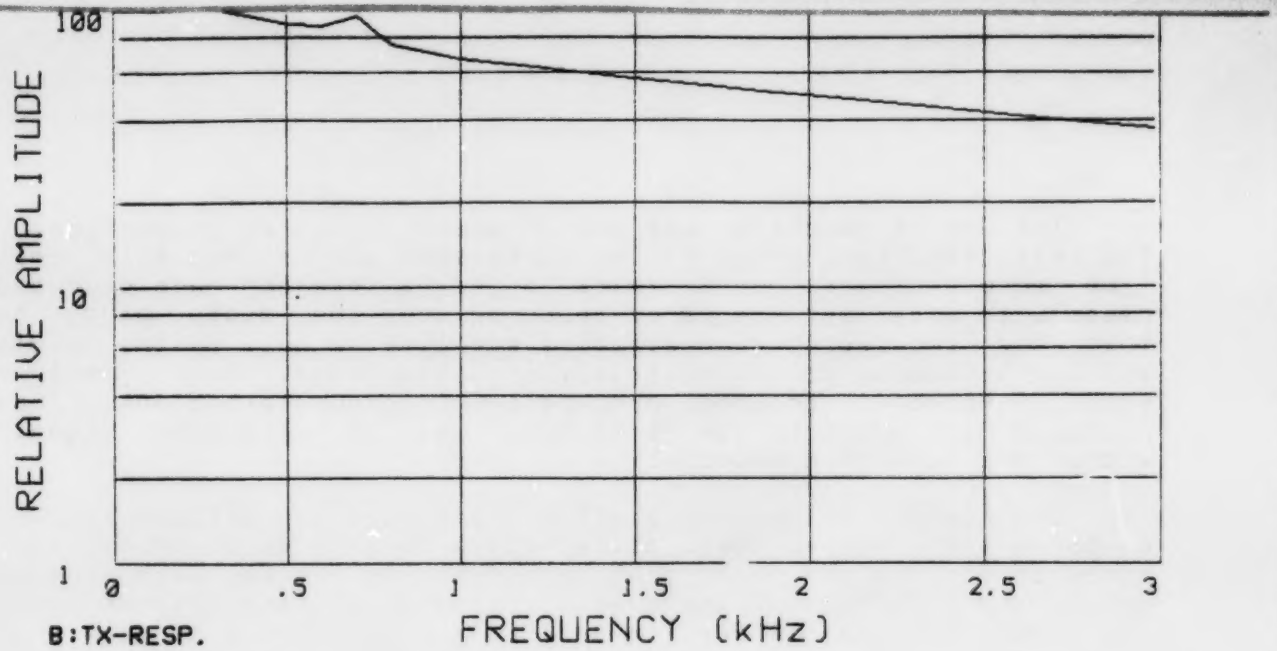


FIGURE 4. Frequency response of the transmission side of the field system, showing how the underwater sonar's resonance characteristics at 700 Hz can be minimised with an over-all design.

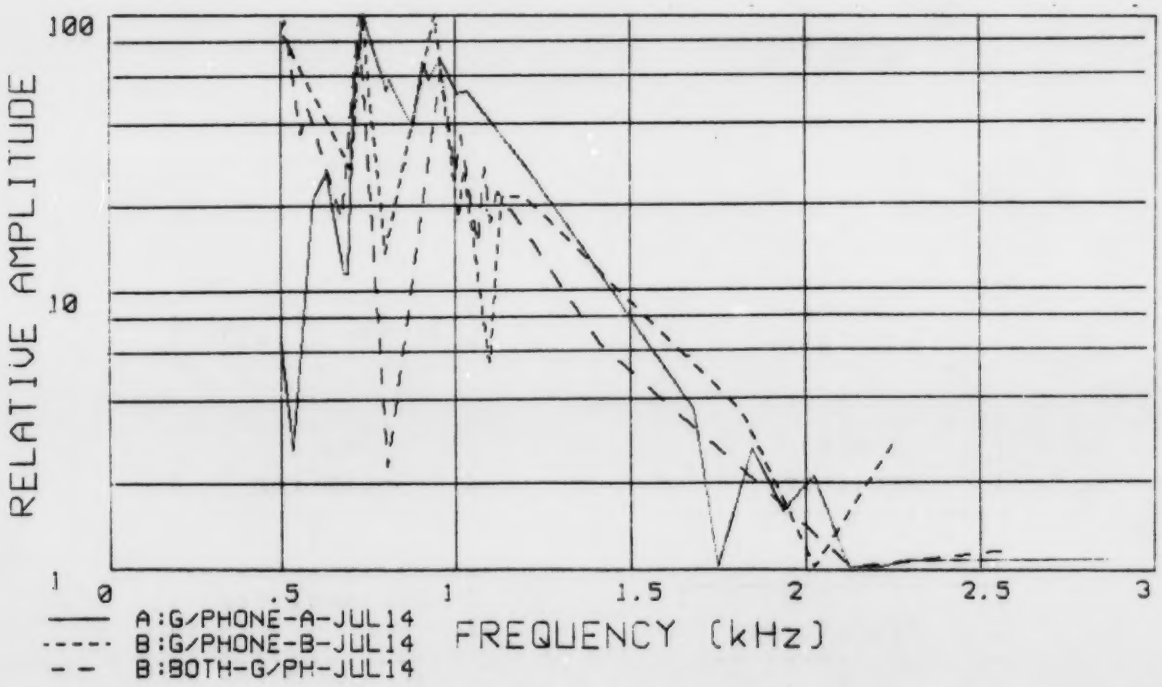
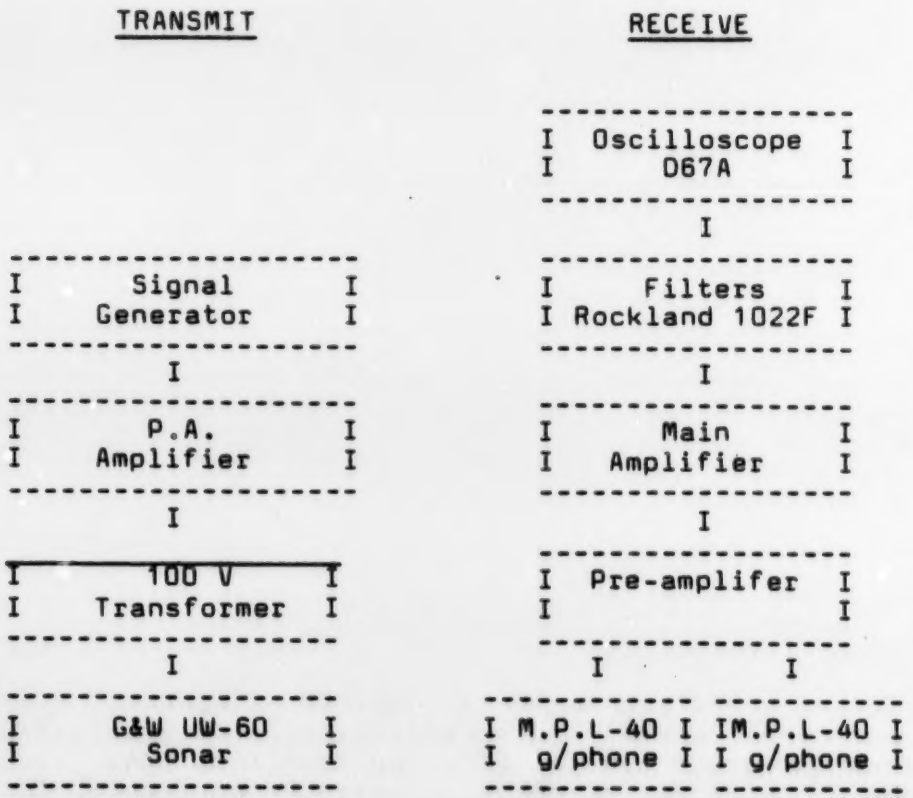


FIGURE 5. Plot of amplitude response against frequency for two identical geophones which are geometrically placed at different distances from the sound source. It is evident that the location of a geophone dictates its response in terms of amplitude, but not at what frequencies they occur. That is solely dependent on the resonant properties of the medium; in this case, ice. It is therefore necessary to remove these amplitude effects by summing both geophone signals together.

The use of geophones was one of several devices investigated. The only other type which proved successful was a magnetic coil type record-player head. Years of hi-fi research have produced heads with excellent frequency response over the audio band, so that the receiver characteristics are limited only by the head's ability to couple to the material, in this case, ice. Previous work by Hudson on acoustic propagation in concrete had shown that a stereo head provides an effective way of detecting signals within the bulk of a material.

In Figure 6, a comparative test was run between an L-40 geophone and a stereo head, placed close to each other on the same block of ice. It was noted that both detected the key harmonics at 650 Hz and 1100 Hz, but the overall response of the stereo head was superior above 1200 Hz, in addition to being more sensitive to minor peaks and troughs. This is due in part to the difference in mount: the geophone integrates over a wide area, while the stereo head samples a discrete point.

Our overall conclusion, therefore, is that the magnetic stereo head offers some interesting possibilities as a means to detect acoustic waves in ice, provided it can be ruggedized economically.



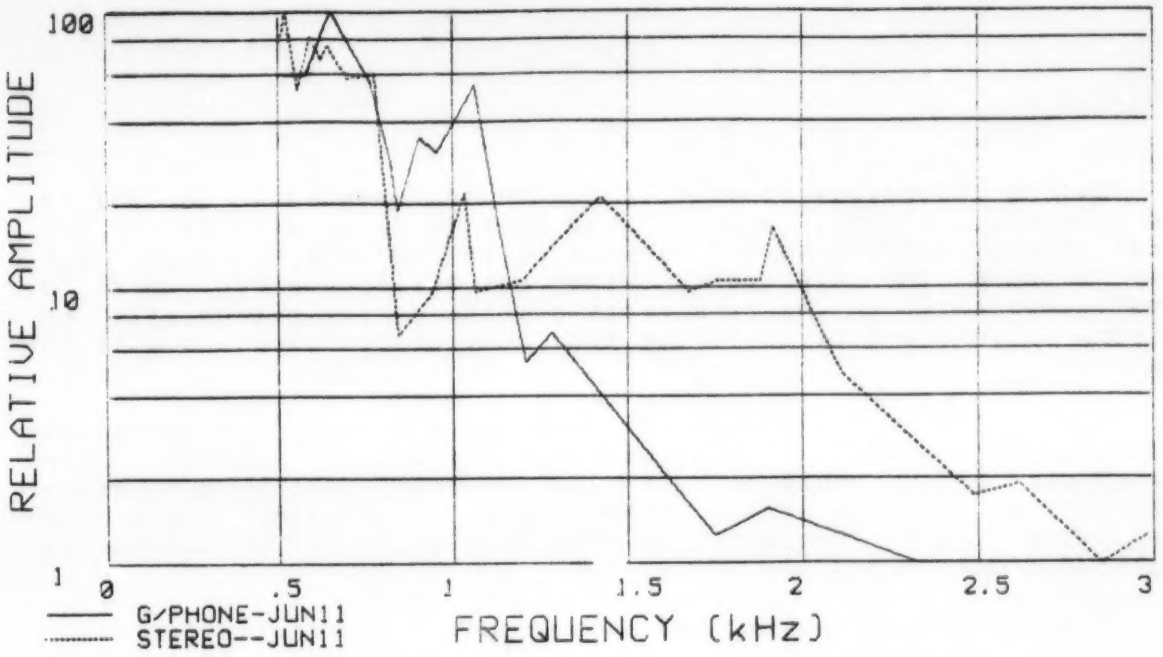


FIGURE 6. Graph showing the relative sensitivities of a seismic geophone and a conventional stereo head cartridge, with respect to frequency. Notice that the stereo head gives better sensitivity at high frequencies, together with sharp peaks at resonance. Despite these advantages, the cartridge was superceded by the geophone, which offered ruggedness and high signal sensitivity.

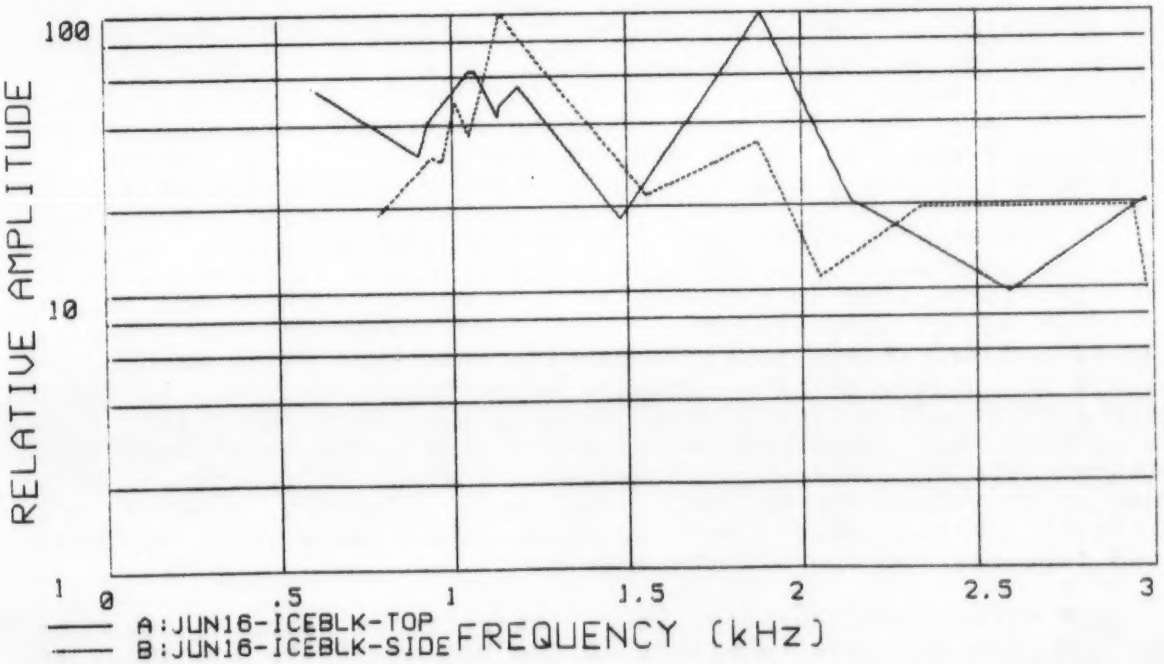


FIGURE 7. Frequency response of two geophones which were placed on top of (A, the solid line) and on the side of (B, the dashed line) an ice block. Because of the confined geometry, both detect the principal resonances, but with different sensitivities, as each receives either horizontal or vertically polarized waves.

During laboratory studies it was found necessary to filter the received signal, due in large part to 60 Hz effects. In the field trials, similar harmonics were noted and were filtered, but only because the electronic system was still dependent on AC (a Honda generator). In the final version, the entire system will be battery driven, and it is likely that only crude filtering will be required.

The filtered signal was monitored on a portable oscilloscope (Telequipment D67A). A typical test involved setting the transducer power amplifier at such a level that no saturation occurred at the receiver, after which the signal generator provided a swept frequency to the system, and the relative amplitudes were noted.

Preliminary acoustic tests were run in a circular tank full of water to establish overall electronic integrity. These were followed by trials on a concrete slipway. Here, the sonar source and hydrophone receiver (see Appendix I for specifications) were mounted on a small float, and the unit pushed out into progressively deeper water. The wedge-shaped water column reduced the number of extraneous resonant peaks, but was nevertheless still cluttered.

Work followed on coupling the geophones to the system and carrying out dry tests. Concrete blocks of large dimensions were used to calibrate the hardware. Trials revealed that the signal source could be sufficiently well coupled to a block, and was sufficiently spherically polarised, that standing waves between all parallel-sided surfaces could be generated, irrespective of the source's position. Nodes and anti-nodes could be traced by changing the relative positions of the two geophone receivers.

A series of field trials were then carried out on lake ice below the Athabasca Glacier, Alberta, and on the glacier itself. When the party reached the area in early June, much of the lake's ice cover had already broken up and the remainder was heavily candled and saturating rapidly. Despite this, the party managed to salvage a piece of ice about a metre thick, and carried out a variety of sounding experiments. As this was the first time that the system had been tested in the field, a number of technical failures were encountered and overcome. Unexpected resonances were found which turned out to be cross-cable coupling between the transmit and receive cables; for field convenience, they had been taped together and run off the same spool.

The effect of surface wave interference was studied by coupling the geophone receivers to the bottom of the ice sheet so that the through-ice compressional waves dominated. It was found that the surface wave peaks could be reduced to acceptable levels by using a pair of receivers with a spacing of approximately a quarter wavelength of the surface wave at mid-frequency (ie. 50

cm).

For the first time, it was noted that there were very pronounced nulls at certain frequencies due to surface and through-ice wave interference. These events exhibited extremely high signal-to-noise levels, and were very frequency specific. To reduce their effect, two geophones were ganged together at the input of the display unit, so that each could have a seperate gain to compensate for its relative position.

Tests were carried out on the main ice of the glacier itself, in an area of approximately 50m thickness (based on the Environment Canada (Inland Waters Directorate) map 8/6, 1980). The tests were inconclusive due to bad weather which hampered the project and led to equipment failure.

Data obtained from the glacier and lake tests are not presented because it was later found that the frequency counter had been operating erratically. As there was no way to back-calculate the correct frequencies, the data sets are of little specific use.

What did develop from the field project was:

1. Surface waves may be effectively reduced on ice.

2. Coupling to ice using the rubber membrane-covered sonar presents no problem.

3. Varying the wave shape appears to have no effect on the penetration.

4. Certain modifications to the basic electronics were carried out, to improve the ease of operation.

5. Resonant amplitude peaks are a minimum of 3dBr above the ambient signal-to-noise level, even on deep ice.

6. The acoustic mismatch at the ice:water interface appears to be fairly important, but not crucial, particularly at the lower frequencies.

Back in the laboratory, it was discovered that the frequency counter had been giving erroneous results. Two blocks of ice were ordered from a local ice supplier to carry out a re-test of some of the acoustic work. Each block measured approximately 85 x 50 x 25 cm.

One of the blocks was stood off the floor on a 50 x 25 cm side; geophone A was attached to the top surface, geophone B was taped to an 85 x 50 cm surface. Figure 7 shows the received amplitudes of the two geophones. Note that both units detected the

resonances at 1150 and 1900 Hz which correspond to the ½-wave dimensions of 83cm and 50cm as expected, but their relative amplitudes are not the same because both devices are preferentially polarised to waves normal to the surface on which they are mounted. As a result, geophone A, which was on the 50 x 25 cm surface, picked up the 1900 Hz peak representing the standing wave between the two surfaces 50 cm apart, while geophone B, mounted on the 85 x 50 cm side, was most sensitive to resonances between the two faces 85 cm apart. Both should also detect the harmonic between the surfaces 25 cm apart (3.8 kHz), but do not because of sensitivity roll-off of the equipment.

What the tests illustrated was that (given an accurate counter):

1. The resonant peaks could be used to measure the block's dimensions.

2. In something as small as an ice block, the sonar is omni-directional, so that beam steering is not possible to any degree.

3. Correct alignment of the goephones is necessary. (This will not be a problem on sea ice.)

4. System response above 2.5 kHz (representing 40 cm of fresh ice) prohibits the use of this technique with the currently available equipment.

At this point, it was considered necessary to conduct tests on a large, thick sheet of ice to determine effective signal-to-noise levels in the acoustic band when the background was not being affected by extraneous peaks due to dimensions other than the top and bottom surfaces.

A decision was made to build a 'pseudo-anechoic' ice chamber which would permit work on ice 'sheets' up to 1.5m in thickness. A simple design was put forward. Two 45 gallon drums were welded one on top of the other. The inner curved wall was lined with closed-cell foam (which does not absorb water) to prevent freeze-bursting during the freezing process, and the inner space was filled with a number of concentrically fitted car tyres. The insides of these tyres were themselves randomly stuffed with pieces of sponge foam.

The overall aim was to create a 1.75m column of ice having a clear central core of 30 cm, and cylindrical sides which were sufficiently broken up accoustically that any sound wave which diverged away from the central vertical axis was likely to be scattered in a random way in the tyres/sponge/foam mixture and would not be reflected back to the surface.

The unit proved to be very successful. At very little expense, an anechoic chamber was produced which was sufficiently insensitive to multiple sound paths, that the principles of deep-ice sounding could be established.

The unit was placed in a local coldroom which had an ambient temperature of about -5°C, and filled to the 95 cm mark. Later a sonar and 2 geophones were placed on the top surface, and the acoustic tests carried out. Figures 8 and 9 show the outputs of tests at 98 cm and 93 cm respectively. It was subsequently felt that the July 11 test (Figure 8) was not on completely frozen ice. The results are therefore included for completeness, but are not discussed.

In Figure 9, there are nulls at 440 Hz, 700 Hz and again at 2125 Hz, which correspond to phase cancellation effects between the reflected horizontal and vertical waves. Solutions for these effects have been derived using 2 approaches: (1) that the two wave sets (vertical and surface) cancel themselves seperately, or (2) that they cancel each other. The latter is more likely, and the solution so derived takes into account this effect. However, the equation cannot be solved because there are an infinite number of solutions depending on the step-out geometry of the geophones, the reflective characteristics of the upper surface of the drum, and the sensitivity/rejection of the geophones to vertically/horizontally polarized sound waves. A solution has therefore not been attempted.

In the field, this condition will not arise, since the surface waves experience no reflecting boundary and only first-order surface cancellations may take place. The solution is therefore straight-forward and, if the discrimination of the geophones to vertical/horizontal waves can be established, the depth of the ice is independent of frequency. This effect will be investigated during Phase II of the project. It may be possible to determine the ice thickness simply by varying the step-out distance of a single geophone from the sound source, and noting the null distances.

In terms of resonant peaks, Figure 9 shows the following:

350 Hz	:	1/12 vertical wavelength
529 Hz	:	1/8 vertical wavelength
1016 Hz	:	1/4 vertical wavelength (masked)
585 Hz	:	1/12 horizontal wavelength
895 Hz	:	1/8 horzontal wavelength
1790 Hz	:	1/4 horizontal wavelength (?)
1570, 2470 Hz	:	horiz/vert phase additions

Points to note are that the resonant peaks are between 10X

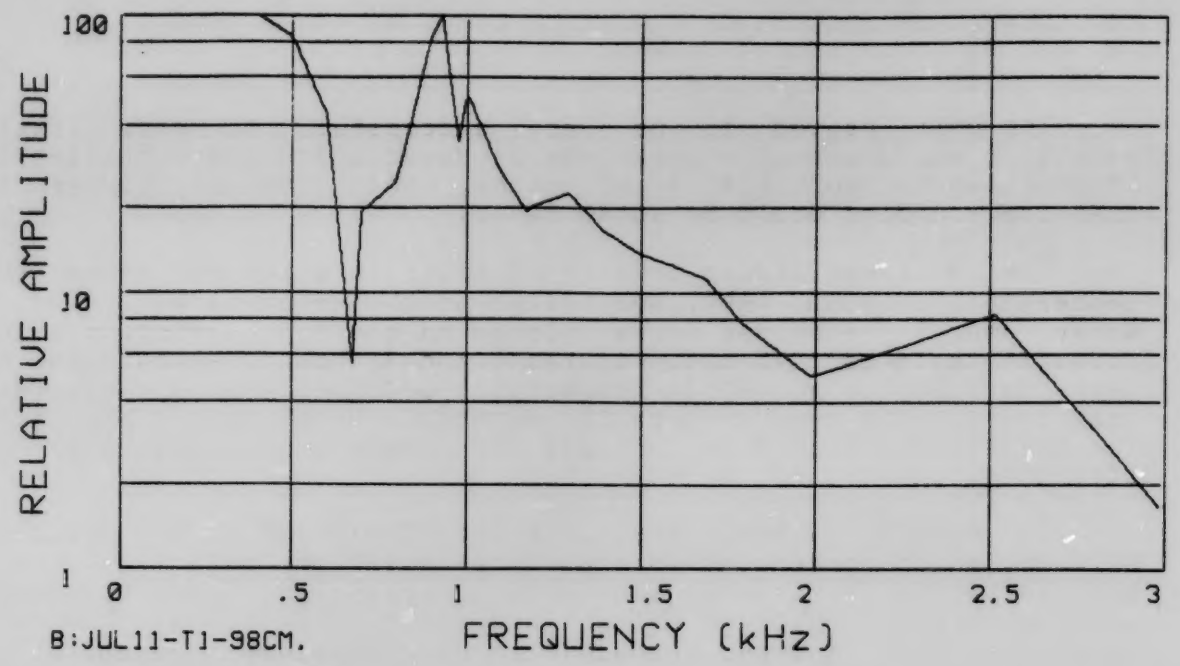


FIGURE 8. Graph of the amplitude:frequency response of an ice block having a maximum dimension of 98 cm length.

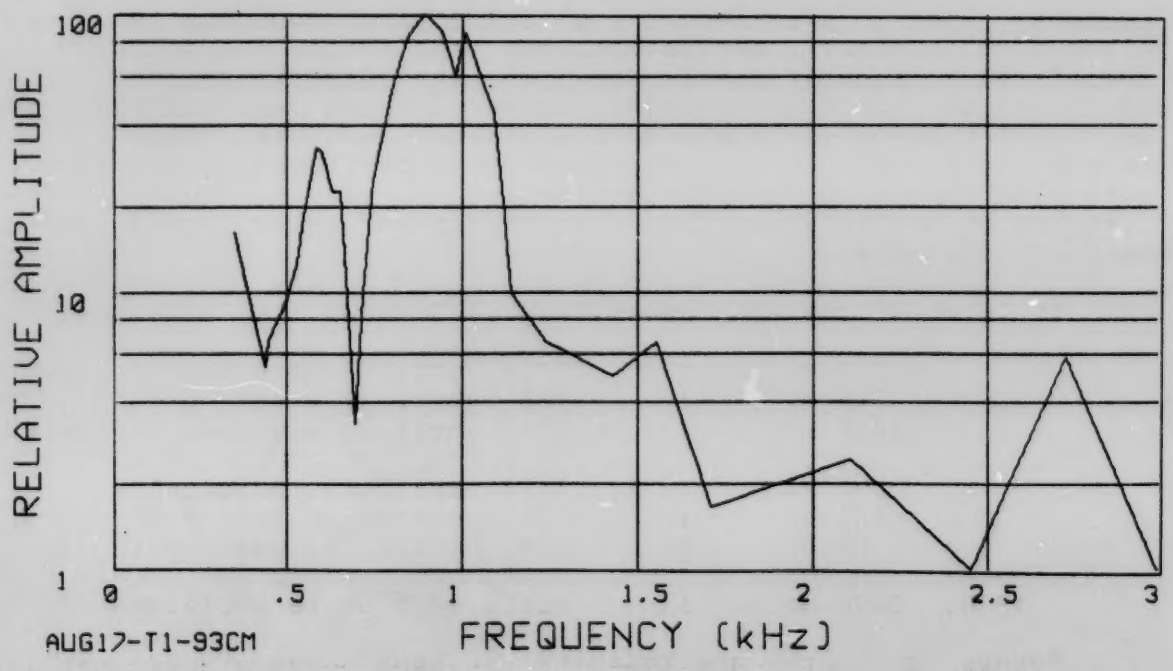


FIGURE 9. Amplitude:frequency response made on an ice core 93 cm deep. Note the relative amplitudes of the peaks with respect to the background levels, allowing easy determination of resonant frequencies.

and 50X the magnitude of the ambient noise level, that they are sufficiently sharp in the frequency domain that accuracies in the estimation of the wavelength (and hence the ice depth) may be made with a ±10% error, and that the system's response above 2 kHz, which is where the first full wavelength frequencies are to be expected, is poor enough to make evaluation difficult.

In Figures 10-12, the acoustic responses obtained from an ice core 175 cm thick are shown. In each figure, the geophone's relative positions were shifted, to establish how much this would affect the output. As would be expected, the differences are quite marked, because the smallest displacement radially within the confined central area of the ice tank means the difference between a surface wave node or antinode. Again, this sensitivity is not encountered in the field: the work at the Athabasca Glacier confirms that although the goephones are sensitive to placement, the surface wave effect is multiplied many times within the confines of the circular boundary of the test tank.

The arithmetic sum of the 3 graphs is shown in Figure 13, but the results are somewhat misleading because the values were not normalized relative to each other prior to addition. As a result, the relative importance of the resonant peaks is not easy to determine, and a 'new' peak is produced at 930 Hz where none existed in reality. However, we may say:

270 Hz	:	1/8 vertical wavelength
530 Hz	:	1/4 vertical wavelength
1100 Hz	:	1/2 vertical wavelength
2200 Hz	:	1 wavelength (?)
610 Hz	:	1/12 horizontal
895 Hz	:	1/8 horizontal
1750 Hz	:	1/4 horizontal

Once again there are pronounced nulls (at 330 Hz and 835 Hz) which are the result of the complex phase cancellation described previously. The overall signal strength of the resonant peaks is high with respect to the ambient, and the crests well defined.

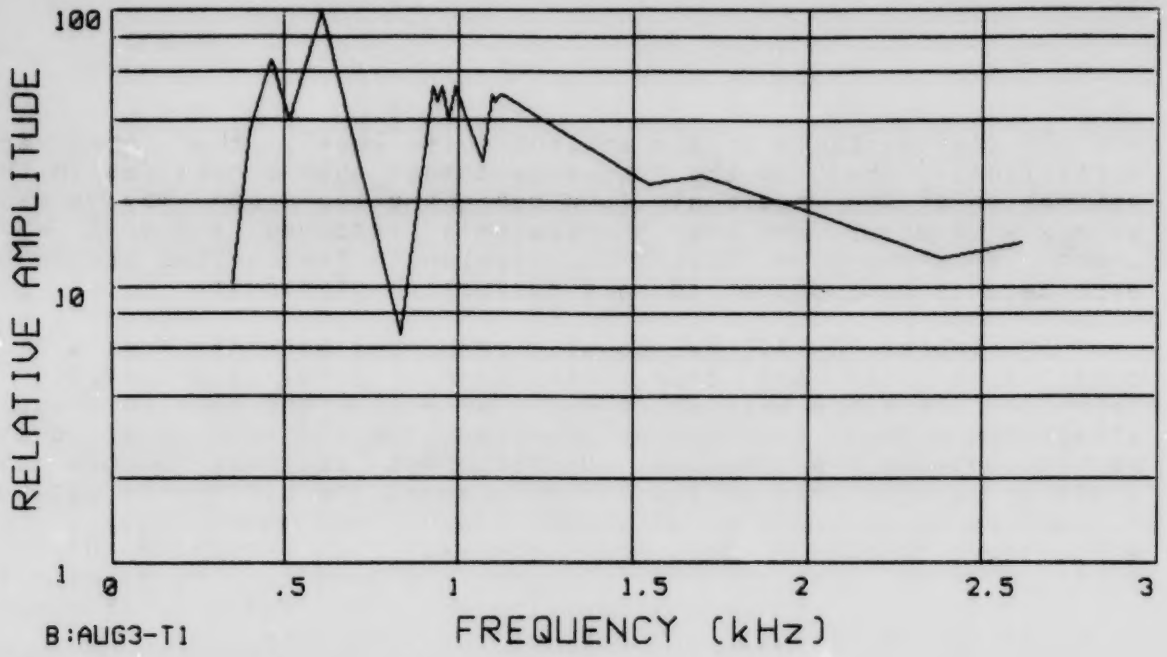


FIGURE 10. Amplitude:frequency response made on an ice core 175 cm deep. For this test, the geophone was located as close to the sounder as possible. Compare the curve with those of Figures 11 and 12, where the geophone geometry has been shifted.

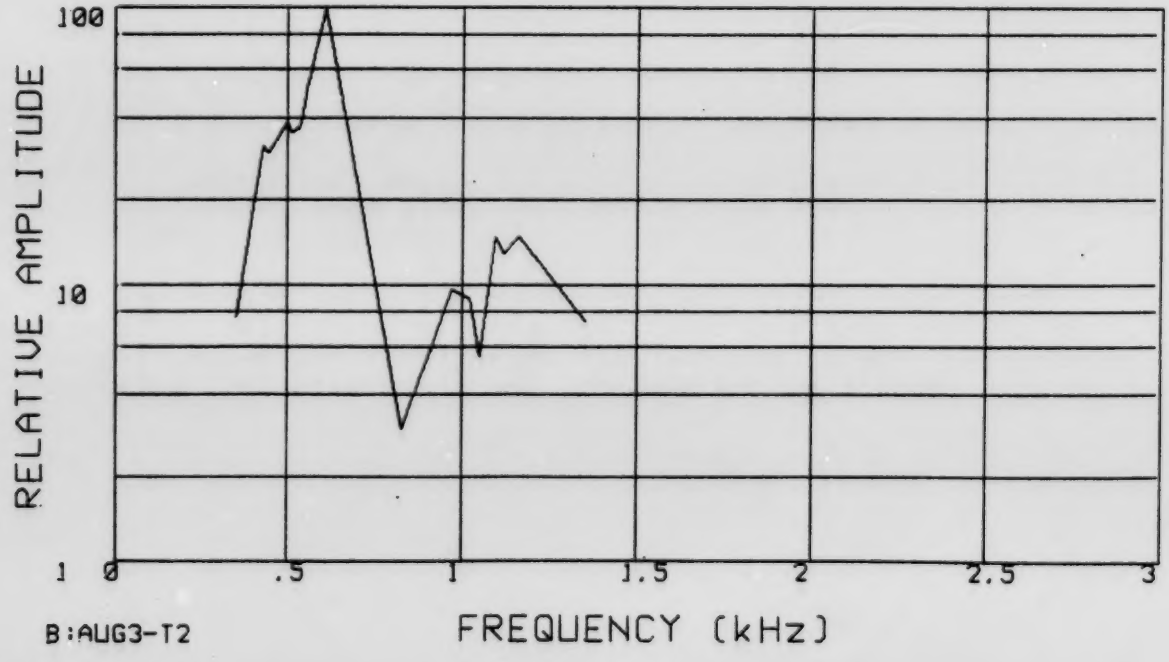


FIGURE 11. Amplitude:frequency response of an ice core 175 cm thick, as per Figure 10. The receiver has been moved to determine the effect of surface wave geometry on the returning signal.

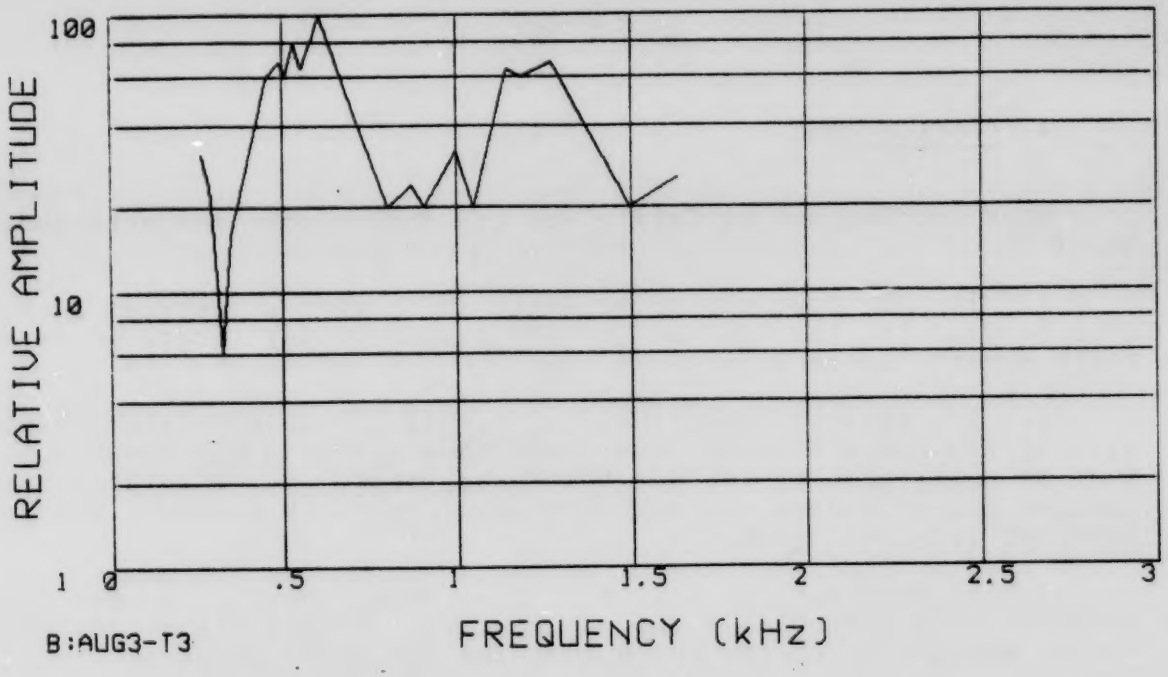


FIGURE 12. Amplitude:frequency plot of an ice core 175 cm thick, with the geometry of the geophone relative to the sound source being changed. Compare with Figures 10 and 11.

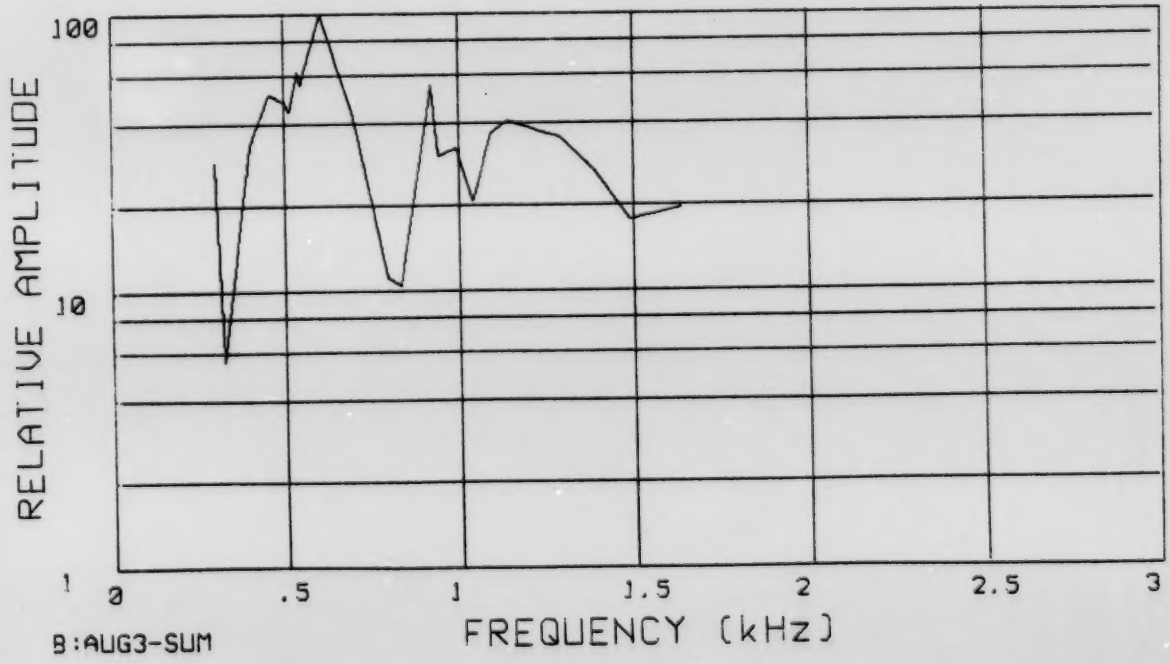


FIGURE 13. Amplitude:frequency response of the sum of Figures 10-12.

4. CONCLUSIONS.

Work carried out by Polar Tech Ltd during this project shows that:

1. It is possible to transmit sufficient acoustical energy into natural ice that reflection and resonance may occur, in even thick sheets (up to 20 m).

2. The resonant amplitudes so formed are clearly discernable against the ambient noise level, and have sufficiently steep edges that an estimation of the ice thickness, based on the relationship between ice thickness and resonant wavelength, is possible with an error of less than $\pm$10%.

3. The hardware system, as it stands, needs to be made smaller, more portable, solely dc powered and have a wider dynamic range, especially at the top end of the frequency spectrum.

4. Further tests need to be carried out on thick ice sheets (with infinite horizontal boundaries) to establish final frequency protocols and to test whether it is possible to establish ice depths using a fixed frequency and varying the step-out distance for phase cancellation.

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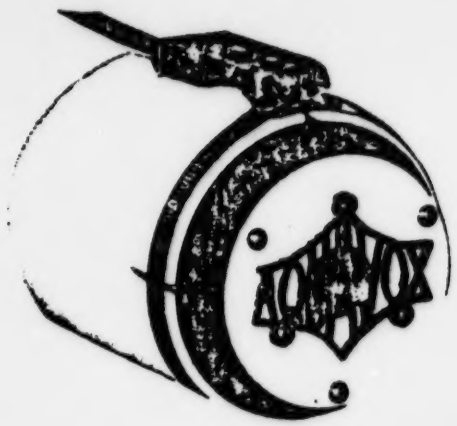
APPENDIX I

Sonar Specifications

This appendix contains details of the underwater loadspeaker/sonar used during the field trials.

AQUAVOX

UNDERWATER LOUDSPEAKER TYPE UW60



This transducer is suitable for very large pools or in open water where clear speech is required or for acoustical research.

Typical acoustical range in reasonably quiet conditions, operating at 50 watts.

Clear speech - 30 metres.

Background music - 80 metres.

For temporary or test use it can be suspended by the side cleat, or alternatively, a cleat can be fitted to the base for suspending diaphragm downwards. For permanent installations the unit can be fitted with a stainless steel grille to suit a standard underwater lighting niche.

SPECIFICATION

MAXIMUM POWER INPUT	50 watts rms.
FREQUENCY RANGE	100Hz to 50KHz.
IMPEDANCE	Nominal 16 ohms
MAGNETIC SYSTEM	Permanent magnet.
MAXIMUM OPERATING DEPTH (airbag pressure compensation)	50 metres.
DIMENSIONS	Overall diameter 125mm. Overall length 150mm. Weight in air 4Kg.
FINISH	White plastic. Cable grey twin PVC covered, length to customer's requirements.

These specifications are subject to alteration without notice.

NOTE The loudspeaker must not be contaminated by strong chemicals if they are used for cleaning the pool, tank or associated equipment.

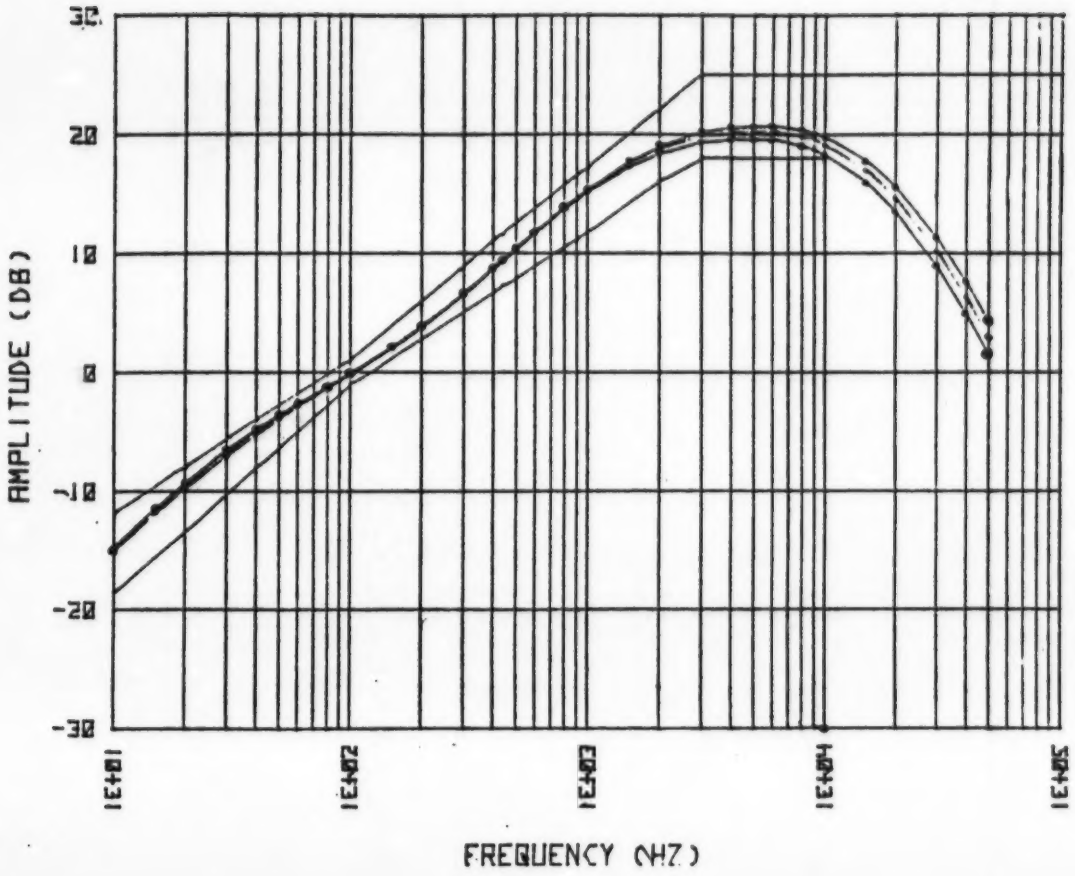


FIGURE I.1(A) Measured response of a Hermes Sonabuoy Hydrophone and pre-amplifier recorded at 30 metres of water depth. Calibration reference hydrophone was a Gould CH-1A Serial No.2280 device.

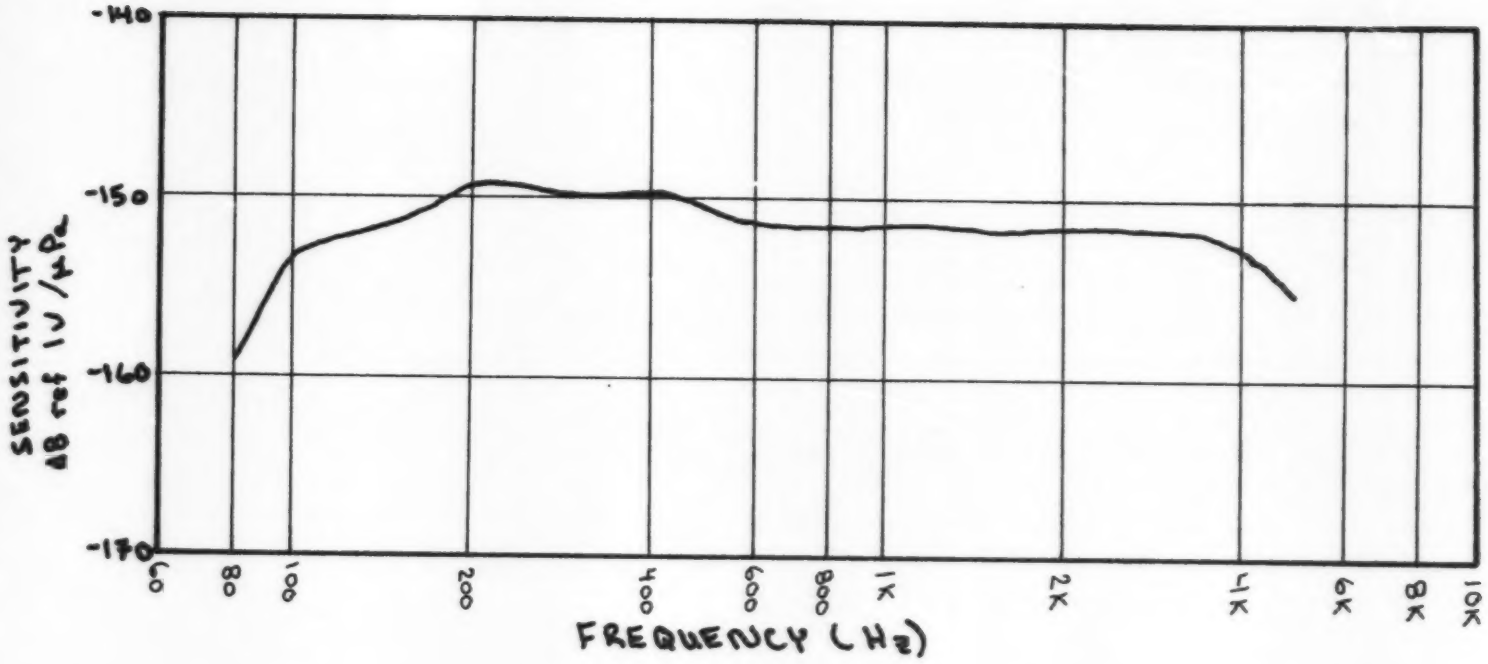


FIGURE I.1(B) *Frequency response of the Hermes hydrophone recording system. The response is designed to fit U.S.Navy specifications, and is not ideal for ice acoustics. Nevertheless, the availability, cost and ruggedness of the units make them a useful reference device during field trials.*

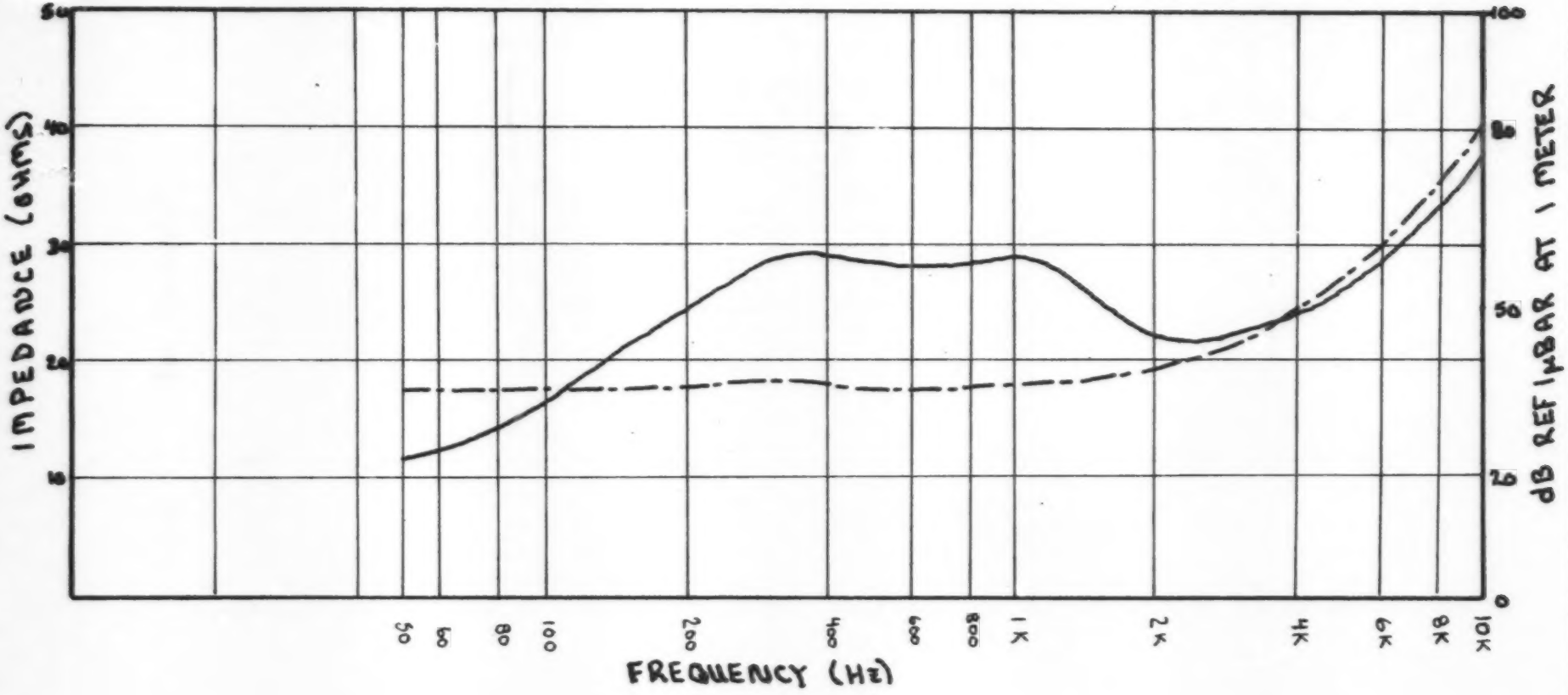


FIGURE I.2 Frequency response of the Gearing & Watson UW-60 underwater loudspeaker used during the field work. This curve was generated at the AMTE acoustic tank in England, for a constant current into the speaker of 1 ampere. The dashed line represents the unit's impedence, the solid line is the pressure level at 1 metre measured in dB referenced to 1 microbar. The curve shows very good overall response in the acoustic band. The pressure curve should be compared with the response measured at the Defence Research Establishment, Pacific, of the same unit, as shown in Figure I.3. (Note: 0 dB ref 1 microbar = 100 dB ref 1 V/micro-Pascal.)

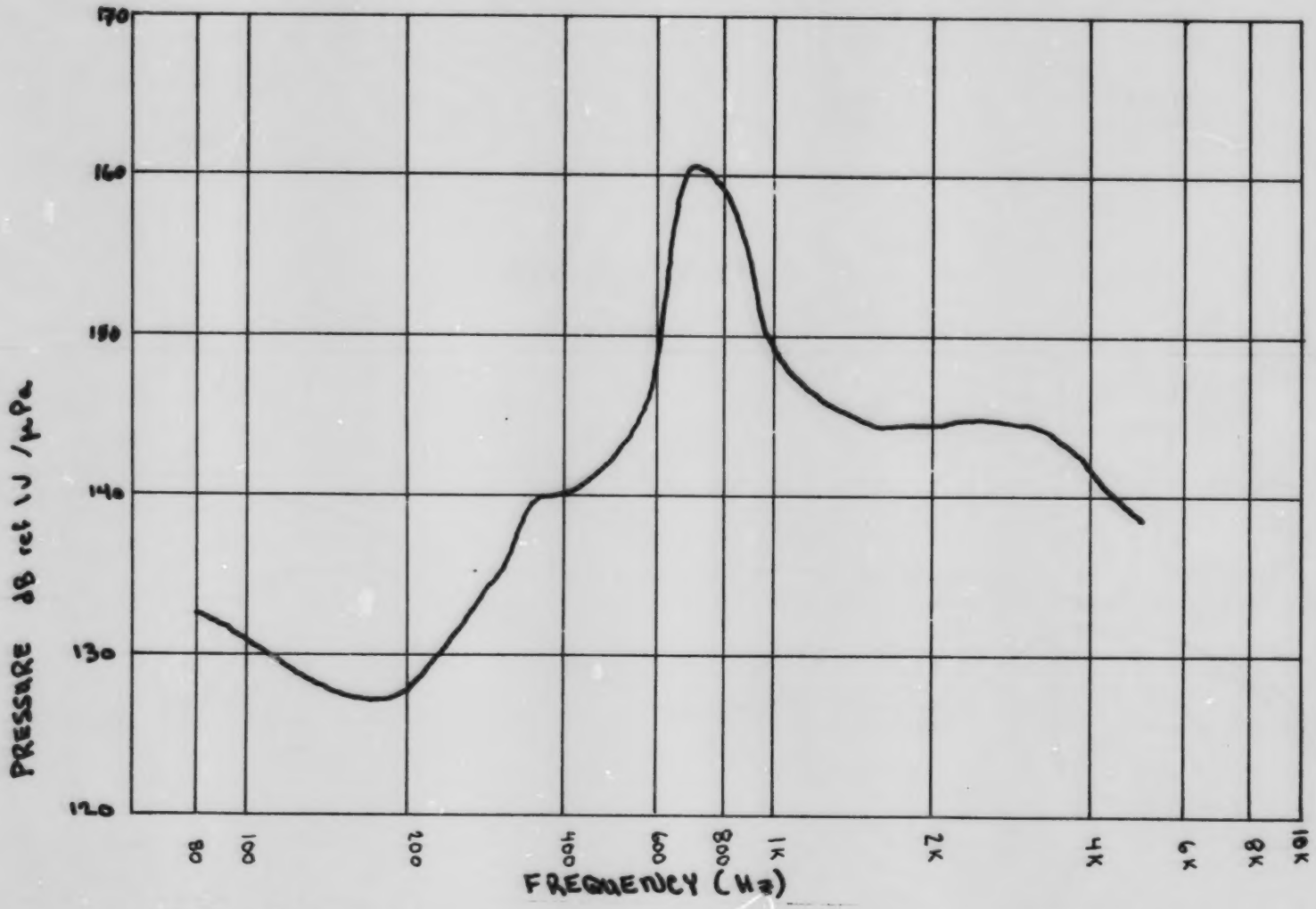
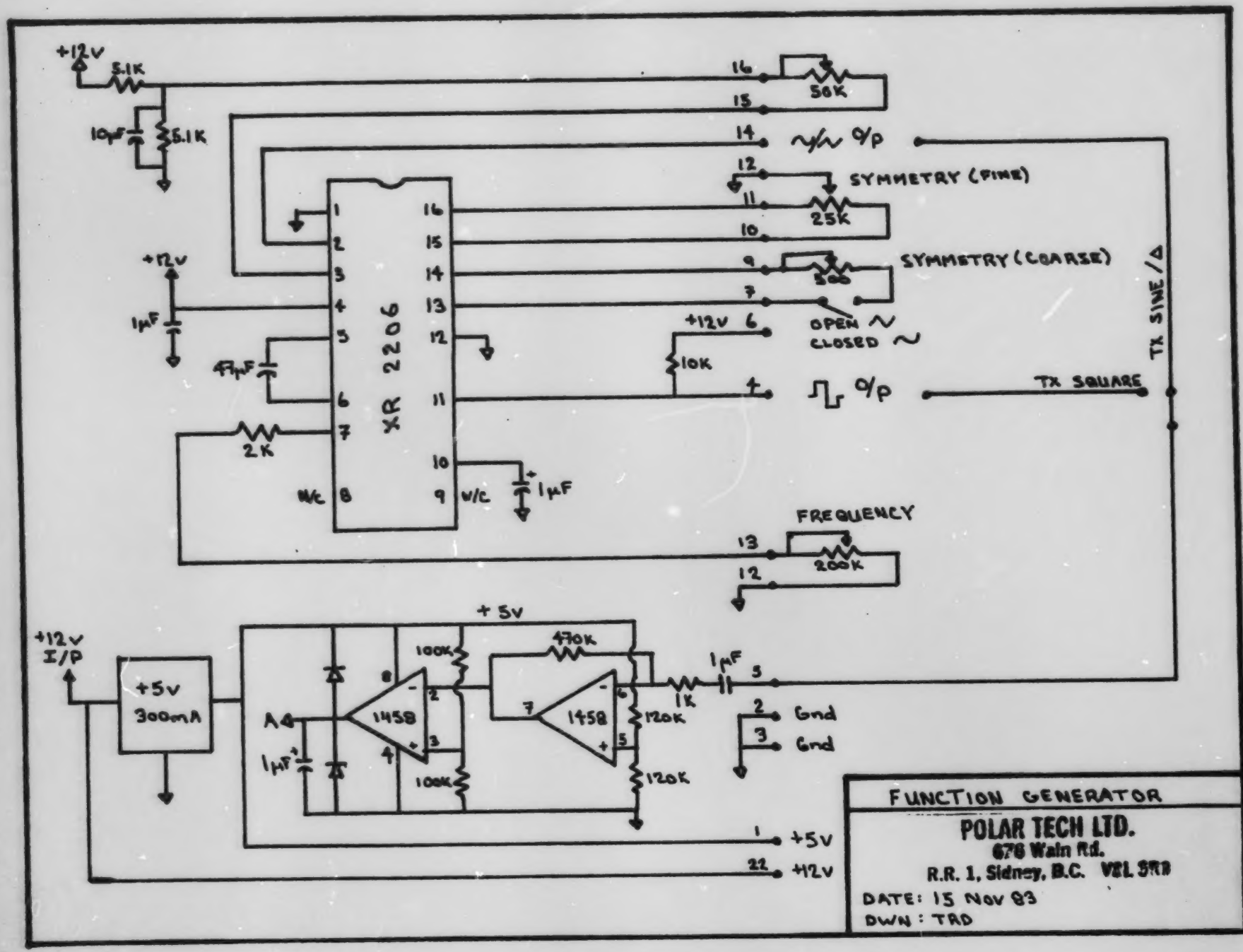


FIGURE I.3 Frequency response of the Gearing & Watson UW-60 underwater loadspeaker measured at the Defence Research Establishment, Pacific. Water depth was chosen at 40 meters to reduce reflection effects. The curve is for 1 ampere rms current into the device with no line transformer. Note the substantial deviation from the curve of Figure I.2, particularly at 700 Hz and [illegible] kHz


+12V
5.1K
10μF
5.1K
16
15
50K
14
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12
SYMMETRY (FINE)
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25K
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9
SYMMETRY (COARSE)
500
7
OPEN ~
CLOSED ~
+12V
1μF
47μF
XR 2206
6
10K
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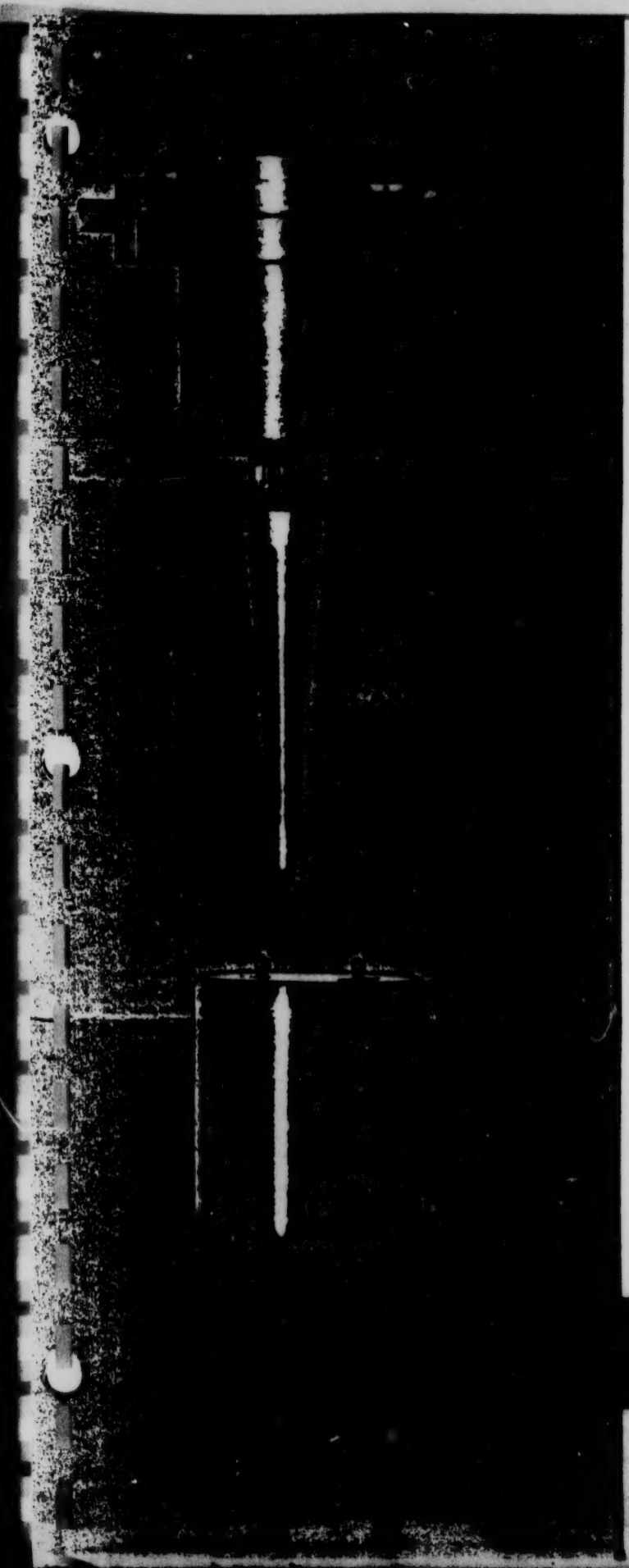
TX SQUARE
TX SINE/Δ
2K
10
M/C
8
9
V/C
1μF
FREQUENCY
13
200K
12
+5V
+12V I/P
+5V 300mA
100K
470K
1μF
5
1K
A
1458
1μF
100K
120K
2
Gnd
3
Gnd
120K
1
+5V
22
+12V
FUNCTION GENERATOR
POLAR TECH LTD.
678 Wain Rd.
R.R. 1, Sidney, B.C. V8L 5R8
DATE: 15 Nov 83
DWN: TRD

APPENDIX II

Geophone Specifications

This appendix contains details of the high frequency geophones used to detect acoustic responses within the ice sheet.



The L-40 is a quality, high resolution geophone. The same proven design techniques known so well in Mark geophones was used to produce this high performance geophone.

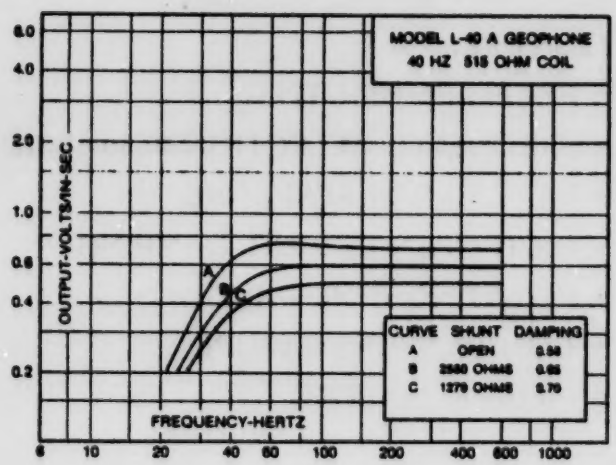
A wide selection of frequencies are offered - 40, 50, 60 and 100 Hz. Standard coil resistances are available for your selection.

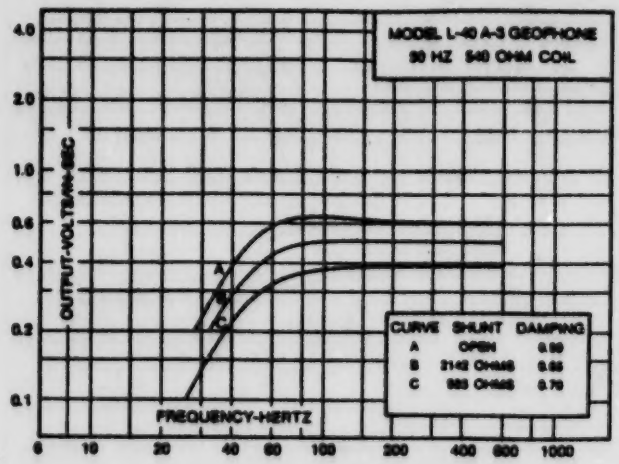
FEATURES:

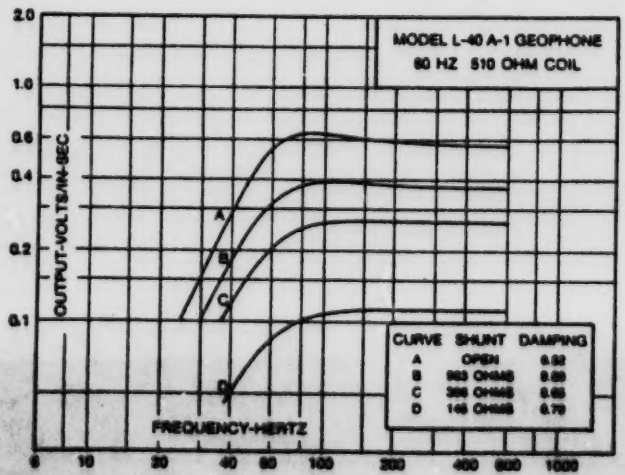
- **EXCELLENT OUTPUT**
- **FREQUENCY SELECTION 40-50-60-100.**
- **VERY CLEAN RESPONSE**
- **HIGH OPEN CIRCUIT DAMPING**
- **ROTATING COIL - RUGGED**
- **COMPACT - MINIATURE**
- **FIELD RELIABLE**

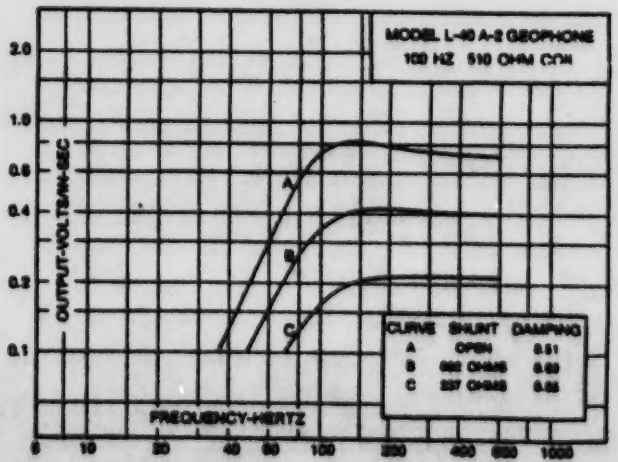
HIGH RESOLUTION
GEOPHONE

	L-40 A	L-40 A-1	L-40 A-2	L-40 A-3
STANDARD FREQUENCY RANGE	40 Hz	60 Hz	100 Hz	80 Hz
FREQUENCY TOLERANCE	± 7%	± 7%	± 7%	± 7%
STANDARD COIL RESISTANCE ± 10% (OHMS)	335, 515, 835	325, 510, 780	325, 510, 780	345, 540, 830
DISTORTION @ RESONANCE, @ 0.7 IN/SEC	0.2% MAX	0.2% MAX	0.2% MAX	0.2% MAX
TRANSDUCTION CONSTANT, V/IN/SEC	$0.031\sqrt{Rc}$	$0.025\sqrt{Rc}$	$0.031\sqrt{Rc}$	$0.026\sqrt{Rc}$
OPEN CIRCUIT DAMPING	$\frac{23.0}{f}$	$\frac{31.4}{f}$	$\frac{50.8}{f}$	$\frac{29.5}{f}$
COIL CURRENT DAMPING	$\frac{16.7\ Rc}{f\ (Rc + Rs)}$	$\frac{13.85\ Rc}{f\ (Rc + Rs)}$	$\frac{20.5\ Rc}{f\ (Rc + Rs)}$	$\frac{14.9\ Rc}{f\ (Rc + Rs)}$
SUSPENDED MASS, GRAMS	7.2	5.7	5.7	5.6
CAST-TO-COIL MOTION, P-P INS.	0.080	0.080	0.080	0.080
INTRINSIC POWER SENSIVITY mv/IN/SEC	0.96	0.63	0.96	0.68
BASIC UNIT DIAMETER, INS.	1.25	1.25	1.25	1.25
BASIC UNIT HEIGHT, INS.	1.37	1.37	1.37	1.37
BASIC UNIT WEIGHT, OZ.	5.0	5.0	5.0	5.0









MARK PRODUCTS, U.S. INC.
Area 713/498-0600
10507 Kinghurst Dr.
Houston, Texas 77099
Telex 76-2069

MARK PRODUCTS, LTD.
Area 403/275-3544
1108 55th Ave. N.E.
P.O. Box 73
Calgary, Alberta, Canada T2P-2G9

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APPENDIX III

Field and Equipment Photographs

Photographs showing various aspects of the field work and related equipment.

PHOTO 1. Electronic equipment for the glacier field tests was mounted in the van, and cables run onto the lake and glacier.

PHOTO 2. The sonar (right) was used to set up standing waves in the ice. Two high frequency geophones were used to detect resonances. Here, both have rocks on them to increase their coupling to the ice.

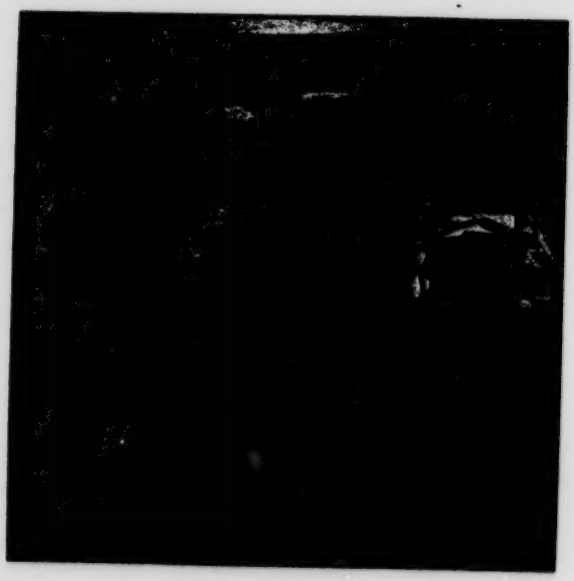

PHOTO 3. To isolate the effect of surface waves on the receivers, a caliper was fabricated to allow a geophone to be attached to the under side of the lake ice (which was here about 45 cm thick). The geophone may be seen attached to the lower arm of the device.

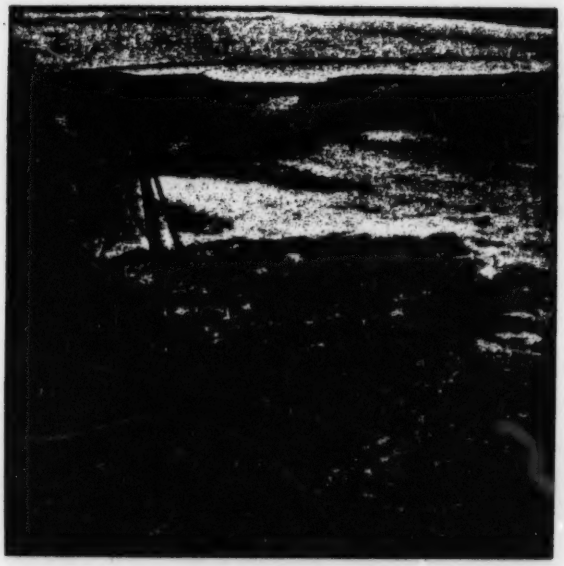

PHOTO 4. The caliper in action. A geophone is in contact with the under side of the lake ice, and almost directly below the sounder. In this way, surface wave effects may be minimised.

PHOTO 5. Part of the problem associated with working on the lake ice was that the spring thaw resulted in the ice being severely candled. This may have affected the resonance characteristics of the ice sheet.

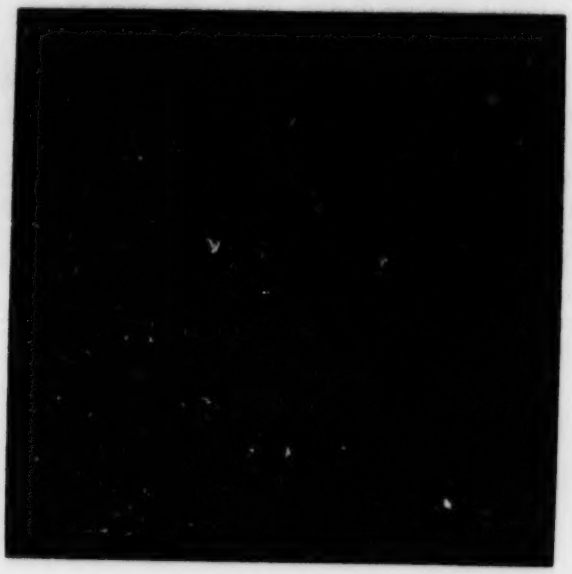

PHOTO 6. While operating on the glacier itself, a Bombi was borrowed from Brewster Bus Line to enable echo soundings to be made at suitable sites, while keeping the electronics dry.

PHOTO 7. Block of ice (covered in towels to shade it) with sonar and geophone during trials in Sidney to recheck frequency counter effects.

PHOTO 8. Sounding through the length of an ice block, with both sounder and geophone on the smallest side. This work resulted in the graphs of Figure 2.